Some Enlightening Case Histories on Lightning Damage

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Significance:
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This paper documents three case histories of damage caused to electronic systems and appliances for direct or nearby lightning strikes to residential structures. Complementary laboratory tests have been performed to narrow down the range of stresses to which the field-damaged equipment were submitted.

These case histories also illustrate the consequences of incorrect bonding of utility connections to one residence, the sensitivity of dispersed electronic systems in the second residence, and incorrect routing of earthing conductors in the third residence.

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SOME ENLIGHTENING CASE HISTORIES ON LIGHTNING DAMAGE

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Abstract: Lightning-related damage stories abound, but it is not always possible to document precisely the mechanisms and scenarios involved when timely, first-hand knowledge is not obtainable. From a collection of case histories accumulated by the authors, three cases are described. Each of the three illustrates a different mechanism leading to structural damage or equipment failure, in ways that might not have been obvious from a casual investigation of the damage or sites, or from second-hand reports.

Keywords: Lightning damage; system interactions; equipment immunity.

1. INTRODUCTION

In an area of Eastern Tennessee, U.S.A., where the three lightning incidents reported here occurred in 1998, the ground flashes over an area of 40 km radius average 22 000 per year. The year 1998 was particularly active, a total of 27 993 ground flashes, or 5,5 flashes/km^2 [1]. These incidents of damage came to the attention of the authors, providing a unique opportunity to document the mechanisms and failure modes of residential electronics.

The first incident involved a small house made primarily of wood where the power service entrance and the cable TV entrance were at opposite ends of the house - the classic error in installation practice — compounded with a violation of ground bonding rules. The second incident involved a residence with an elaborate audio-video system with a central equipment rack distributing signals to speakers and monitors. A third incident was the case of a direct lightning flash to the overhead service of a house, resulting in severe fire damage to the structure.

2. THE CASE OF THE COZY CABIN

At this rural site, a wood-structure residence suffered two failures of video equipment during lightning storms, a few months apart. The owners allowed the authors to visit the site and acquire the second failed TV receiver for a post-mortem examination and tests.

The visit revealed a case of the incorrect but frequent practice of two uncoordinated providers -- the cable TV company and the power company -- installing their service entrance at opposite ends of the house (Figure 1). The consequences of such practice are briefly described in the following.

2.1 The problem of shifting reference potentials

The general problem of shifting reference potentials during surge events has been described in previous work [2]; [3]. A brief description of this problem is given here to place the "*Case of the Cozy Cabin*" in perspective.

In the scenario of Figure 1, a personal computer (PC) is connected to both the power system and the telephone system. The surge current "Surge I" flows from the telephone system toward the common grounding point via the protective device "NID" at the point of entry, and the equipotential conductor. This current produces a magnetic field which couples into the loop formed by the power branch circuit, the telephone premises wiring lines to the PC, and the equipotential conductors. The voltage thus induced in the loop appears across the telephone and power ports, with upsetting or damaging consequences.

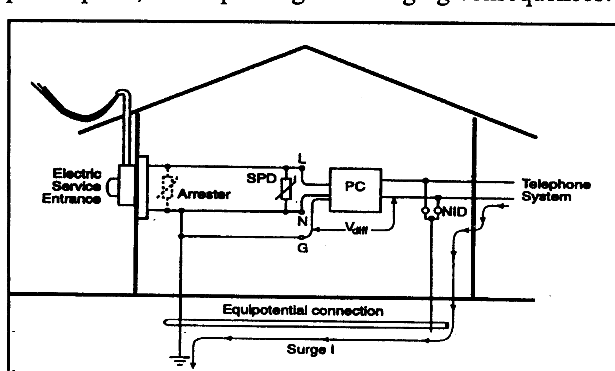

Figure 1 — Scenario for shifting reference potentials between power and telephone systems

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In a laboratory replica of this configuration [2], a peak voltage of 4,3 kV was recorded across the two ports for a typical surge injected at the telephone entrance. A similar situation exists for a surge impinging on the video port of a TV receiver. The tests reported in 2.3 below show that this level can cause damage.

2.2 Cozy cabin site configuration

In the Cozy Cabin installation, the power service entrance was located at one end of the house, while the cable TV service entrance was located at the opposite end. Furthermore, a visit to the site revealed that the cable TV shield was grounded only by a questionable ground rod next to the house foundation (within the drip line, and thus in dry soil, see Figure 2). This cable TV grounding electrode was not bonded to the grounding electrode of the power service entrance, a clear violation of the U.S. National Electrical Code ("NEC", NFPA 70, 1999) [4].

Following the visit to the site by the authors, the local cable TV company was informed of this situation and took what they believed an appropriate action: the incoming cable was first routed under the house, in the crawl space, to allow bonding the shield to the power service grounding connection. From there, the cable was returned to its original point of entry into the house, at the opposite end. This modification did correct the NEC violation but left the arrangement in the topology shown in Figure 1.

However, the interaction was not pursued further with the cable company. A recommendation was made to the owner, to install a surge reference equalizer [5] for each piece of video equipment. After that was done, no damage occurred during the next lightning season. Of course, it is still too early to declare victory over Zeus and Murphy, but encouraging when compared to a previous history of two incidents within a few months.

2.3 Post mortem and surge tests

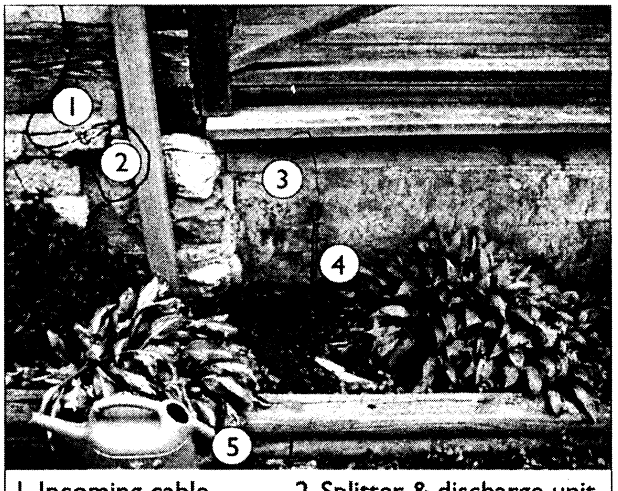
One of the failed TV receivers from the Cozy Cabin was made available to the authors for examination. No evidence of damage was found on the power side of the chassis and the related components, but a clear indication of surface flashover was observed along the insulation of the gap intended to isolate the cable input 'ground' termination (connected to the incoming cable shield) from the shielding can of the tuner (connected to one of the power cord conductors, see Figure 3).

After cleaning the carbonized path of the flashover, a 0,5 μs – 100 kHz Ring Wave was applied in incremental steps between the two conductors of the power cord, bonded together, and the shield connector of the cable input: flashover occurred at 2 kV. By removing the material to a greater depth and covering it with epoxy, the gap did withstand a greater level, and failed at 2,5 kV. That flashover occurred at another part of the original insulation, thus providing valid information on the original withstand capability.

2.4 Conclusions from the Cozy Cabin

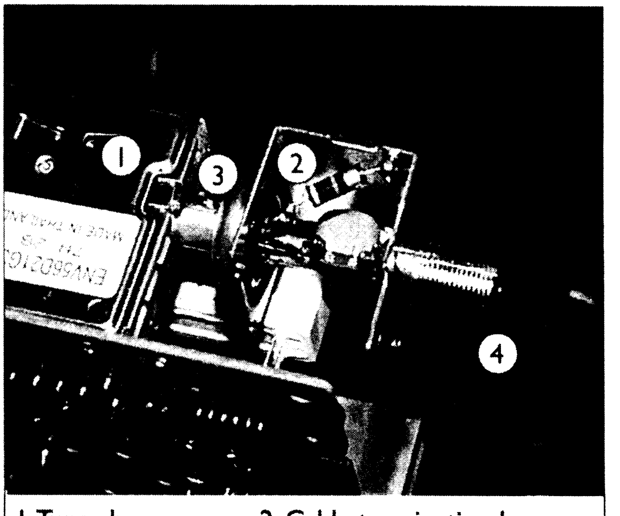
This case study illustrates the classic situation of separate service entrances, compounded with incorrect bonding. The examination and test demonstrate that at least 2,5 kV were developed across the power port and the cable TV port of the receiver under a condition of distant or nearby lightning strike

Another significant finding from this case history is the anecdotal confirmation of allegations that cable TV installation practices prevailing in many residential situations might be in violation of the U.S. National Electrical Code. This violation made even more hazardous the now well-recognized occurrence of undesirable separation of the service entrances.



1. Incoming cable 2. Splitter & discharge unit
3. Grounding wire 4. Ground rod
5. Watering can (for plants, not ground rod!)

Figure 2 — Cable TV entrance



1. Tuner box 2. Cable termination box
3. Insulating gap 4. Incoming cable connection

Figure 3 — Insulating gap at signal input

3. INPUT ISOLATION PRACTICES

Interest aroused by the *Case of the Cozy Cabin* led to a brief survey of what isolation schemes are applied by the manufacturers of video equipment.

Televisions and VCRs are of a similar category of equipment in that they both have the same input ports: ac power, and video (antenna or cable), for which the 'ground' reference can be raised to different potentials during a surge event. The power port has no direct connection to the equipment grounding conductor because a two-prong ac plug is used. However, at the service entrance, the neutral — one of the two conductors of the cord — is bonded to the ground bus of the service panel. The video input is referenced to ground via a connection to a grounding rod outside the residence and (per the NEC [4]), a bonding conductor.

Manufacturers use various techniques to isolate these two ports from each other inside the equipment. Surge tests were conducted on five televisions and three VCRs to determine the voltage level at which spark-over would occur between the power port and the video port. Using a 0,5 μs - 100 kHz Ring Wave, incremental steps of 500 V were applied between the power port and the shield of the video input port.

The units that had isolation built into the video port sparked-over at the series capacitor of the video port. The breakdown voltage level was approximately 2,5 kV in these units. Units in which the power supply outputs were electrically isolated from the inputs via transformers fared better. One sample survived and performed normally after all surge tests. Physical size of the transformer seemed to have some impact on the results. Larger transformers seemed to tolerate surges better than smaller ones.

Based on this small number of VCR samples, a general observation is that VCRs use power supply transformers as isolation, similar to the newer TV sets, and do not have isolation between the cable or antenna input and the tuner chassis. This type of isolation scheme withstood higher surge voltages than the isolating ring that can be found in older television sets and serving to isolate the chassis of the set from the ('grounded') shield of the signal cable.

4. THE CASE OF THE RAMBLING RESIDENCE

An expansive residential estate, located in the same general area as the Cozy Cabin, was the scene of a lightning incident where a tree adjacent to the house was struck (and subsequently died). Extensive damage was inflicted to the audio-video components that are connected to a central rack, and are located throughout the residence and its surroundings (large patio and swimming pool, with outdoor lighting and audio speakers).

The home owners graciously allowed the authors to visit the residence and observe the configuration of the system in an attempt to better understand the mechanisms leading to the damage. They also made available to the authors the complement of damaged or presumed damaged equipment that had been replaced thanks to their insurance. Thus, this case history, unlike most lightning incidents, offered an unusual opportunity for documenting the process and consequences.

Three activities were undertaken to better understand the mechanism and verify some hypotheses:

1. Bench examination of returned equipment and surge testing of undamaged equipment;
2. Site visit of the residence;
3. Laboratory coupling of electric field stress into a remote speaker-to-amplifier connection.

4.1 Bench Examination

Bench tests for each electrical appliance began by plugging it into a 120-V a.c. outlet. Physical signs of normal operation were noted such as illuminated displays, response of controls, audio/video output. The equipment cover was removed for an internal inspection. In most of the equipment, physical damage such as a burned-out transistor was very apparent. Table 1 lists the home entertainment equipment that were submitted, and their condition.

A significant finding was that all of the power supplies in the equipment were functional, indicating that the lightning surge either did not enter through the ac power port, or was not severe enough to cause damage to the power supplies.

Table 1 Equipment submitted for bench tests

Qty.	Equipment	Condition
1	Stereo tuner/amplifier	Illuminated display was not working
3	Digital satellite system receiver	Damage to telephone control circuit
2	Twelve-channel integration amplifier	Damage to power transistors
12	Indoor speaker	Woofer damaged
4	Indoor/outdoor speaker	Woofer damage on all but two units
1	Independent color TV receiver	No damage

The examination and, as appropriate, tests revealed the following conditions:

- Except for its non-operational display, the stereo tuner/amplifier appeared undamaged.
- The visible damage to the digital satellite receivers was nearly identical in all three units. Apparently, the surge had entered through the telephone port and had damaged the small surface-mount electronics that make up the modem circuit. However, because the satellite receivers could not be operated without their antenna and code-reading cards, the extent of the functional damage could not be determined
- The two 12-channel amplifiers had sustained damage to their output transistors that drive the speakers. The power supplies and fuses were not damaged. Furthermore, it was found that some speaker outputs were still operational. This situation suggested a possible mechanism that damaged only some of the output transistors, and therefore not attributable to a "power-line surge." In turn, that hypothesis was later verified by a laboratory test, as described in 4.3 below.
- Speakers, tested by connecting them to an amplifier that was known to be functioning properly, were found to have their woofers damaged, but the tweeters still operational.

Other electrical appliances in the house including television sets and VCRs not connected to the centralized system were not included in the returned package and therefore presumed as not damaged. This finding confirms the conclusion that the long leads interconnecting the distributed system components acted as energy collectors, feeding the induced voltages or currents into the communications ports of the equipment.

4.2 Site Visit

The purpose of the visit was to look for clues to explain the specific damage that was observed in some of the equipment. The following observations were made:

- Approximate distances between the lightning strike and affected equipment
- Location and grounding at the service entrances of cable TV, power, and telephone
- Other wiring and general installation practices

The overall physical layout of the house, damaged tree, and electronic equipment are shown in Figure 4. The tree that was struck is much taller than the house and is the tallest of the trees in the immediate area. The bark was stripped from the tree trunk for most of its height. The tree trunk is only approximately 15 m from the house and even closer to the patio, where some of the audio speakers were installed. Outdoor speakers are also located in the pool area and connecting walkways.

In the audio amplifiers, as noted above, the power supplies of the units were not damaged, but their output transistors that drive the speakers and the speakers themselves were damaged. Thus, it was speculated that the surge energy had been coupled into the speaker wires, which are probably very long and very near to the lightning strike, rather than as a "power-line surge."

The visit to the installation verified this theory. The home entertainment equipment, including amplifiers, is centrally installed in the basement of the house. Speakers are located throughout the house, the patio, and the swimming pool area. The wire length between the outdoor speakers and the central amplifier is about 30 m, and some of the wires run within 10 m of the tree trunk.

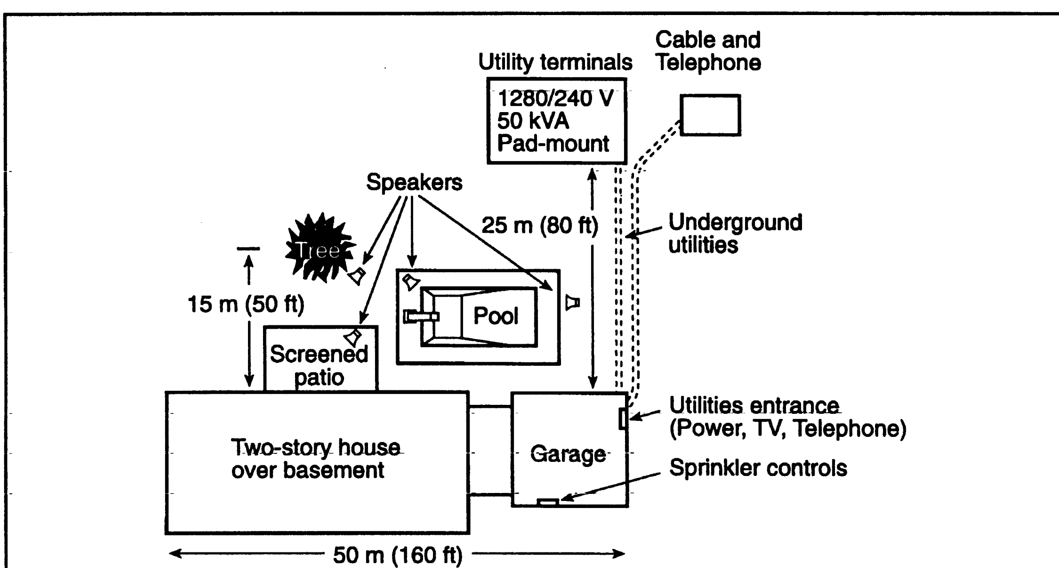


Figure 4
Schematic configuration of the Rambling Residence

4.3 Laboratory Coupling of Electric Field

To validate the hypothesis of a failure mechanism involving the coupling of electric field energy into the speaker wire run, a qualitative laboratory test was staged, using the surviving channel of the amplifier to drive a speaker. An audio signal from a tape deck was fed into the amplifier input to monitor its operation during the test. A conventional Marx impulse generator at the NIST High-Voltage Laboratory was used to apply a 1,2/50 μs high-voltage field between two parallel plates, each 2 m x 1 m.

A length of 5 m of speaker wire feeding the audio output from the system audio amplifier was sandwiched between the two plastic foam sheets separating the lower (grounded) plate, to which the amplifier chassis was bonded, from the upper (impulsed) plate. The effective length of the wire was increased by connecting to each wire a piece of foil of about 0,02 m^2, simulating the increased capacitance effect of about 50 m of wire. Both the amplifier and tape deck were isolated from the power supply ground by an uninterruptible power supply.

The impulse was applied in increments. At 70 kV, a flashover occurred between the two plate edges, ***but not involving the speaker wire***. Immediate failure of the amplifier output circuit was noted. From this anecdote, we conclude that the rapid field change associated with the flashover did have the capability to couple enough surge energy into the capacitance divider of wire/ground plane and cause destructive failure of the output transistor effectively connected across that capacitance. Such a scenario can be considered a reasonable emulation of the circumstances surrounding the "Lightning Incident at the Rambling Residence."

4.4 Conclusions from the Rambling Residence

The qualitative laboratory demonstration of coupling energy into the speaker wires provides one more piece of evidence that electronic appliances can be damaged by surges impacting their communications port, to the point that expecting protection by simple application of SPDs on the power port is not enough, and comprehensive protection is a necessity. In this case, there was no evidence of any damaging surge introduced by the power supply connection of the residence.

5. THE CASE OF THE STANDARD SUBURBAN

5.1 The aftermath

In this case, which occurred in a suburban, semi-rural hilly area, the post-strike investigation revealed that the overhead service drop to the house (involving a span of about 20 m across the street) had been severed by melting at the point of strike. From there, the current traveled to the revenue meter (typically on the outside wall in U.S. practice), where a ground conductor is normally installed with a short run to the earthing electrode of the house. Instead, according to the practice when constructed in the 1970s, a cold water pipe was allowed to be the main earthing electrode. In this case, the conductor for the earthing electrode entered the garage and was routed upward near the ceiling with several bends before it was bonded to a copper water pipe. Without any better path to earth, the lightning current had apparently followed the same route, severing the bare conductor while seeking the well-grounded water pipe (see Figure 5).

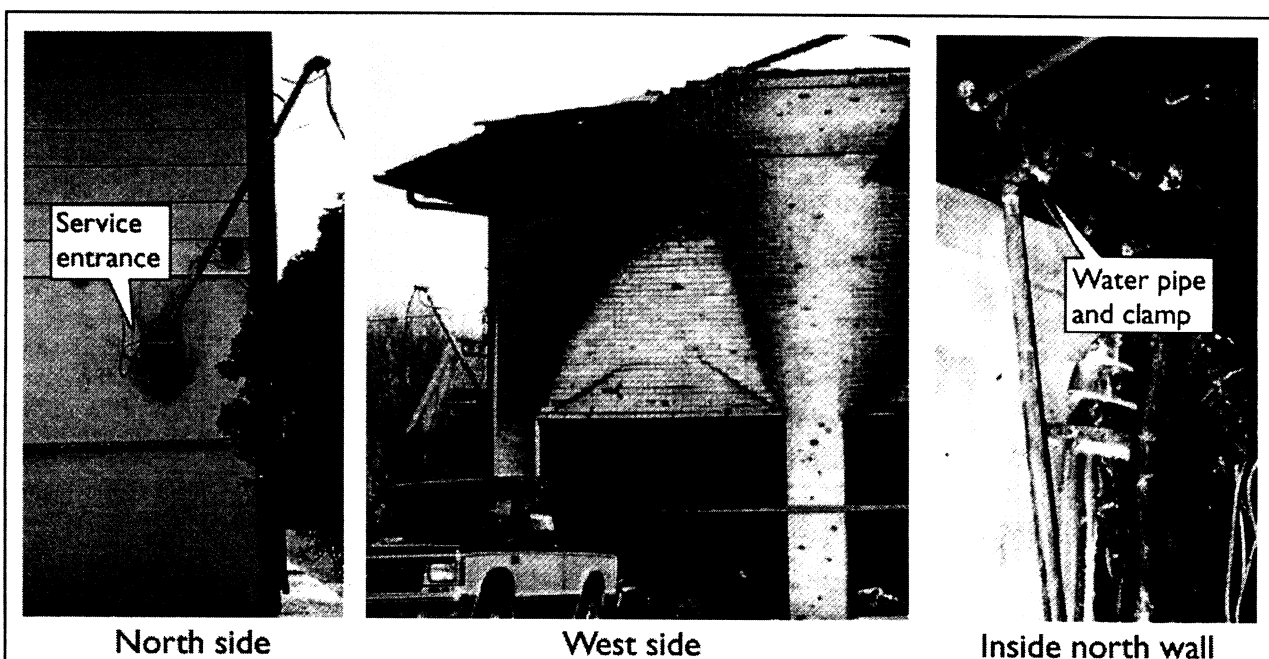


Figure 5 — The Standard Suburban aftermath

As shown in the photographs of Figure 5, the service entrances were overhead and without any direct path to earth. This type of installation would not be approved by current US practice, which requires a direct connection to a driven ground rod in addition to any other supplemental electrodes such as the cold water pipe. One of the main reasons that the practice was modified is the growing use of PVC or plastic water pipe.

On a later visit, the engineers who made the first visit were allowed to visit the repaired house. Indeed, the new service grounding point includes not only the electric power but also the telephone and cable company. The new water piping is PVC, and a driven ground rod has been installed as the primary grounding electrode.

This new arrangement (Figure 6) reflects a recently issued recommended practice [6] which, in addition to the NEC minimum requirements for safety, calls for inter-system bonding of all utilities serving a residence, and this by having all the utility connections next to each other.

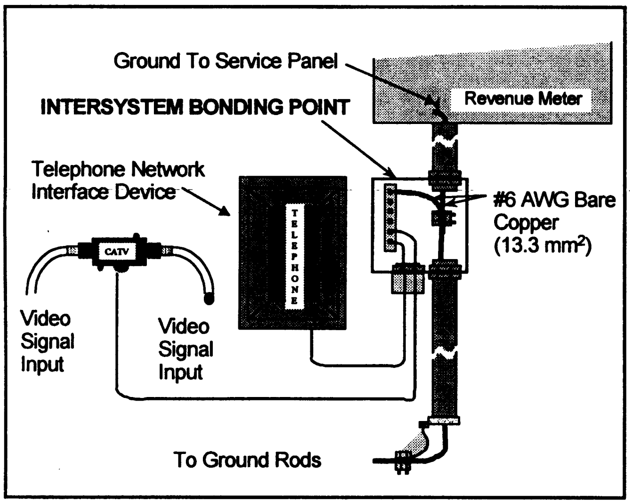


Figure 6 — Recommended intersystem bonding

5.2 Conclusion from the Standard Suburban

Architects and builders, guided by up-to-date codes, can provide appropriate grounding practices in new construction. Surge-protective devices at the service entrance can provide a path from ungrounded conductors and equalize voltages between these conductors. The practice is recommended as the first level of protection from surges in the exterior electrical environment.

6. GENERAL CONCLUSIONS

- The *Case of the Cozy Cabin* and related tests confirm the need to pay attention to the problems associated with the surge protection of multi-port equipment. The solution of non-metallic communications media is not yet ready for the consumer market, but an effective mitigation approach is the surge reference equalizer.
- The *Case of the Rambling Residence* and related tests illustrates that the often-cited "powerline surge" cause is not the only scenario responsible for appliance failures. Other ports of equipment, communication ports in particular, can be damaged by surges induced into the cables used for incoming or outgoing signals, and therefore need appropriate protection.
- The *Case of the Standard Suburban* shows that architects and builders have not fully understood the necessity of appropriate wiring and earthing practices. The same lack of understanding by some utility providers was also evident in the *Case of the Cozy Cabin.*
- The recommended practice of intersystem bonding at the service entrance described in this paper is compatible with the requirements of the U.S. National Electrical Code. Codes applicable in other countries might require a different arrangement, but the principles are the same.

7. ACKNOWLEDGMENTS

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